ABSTRACT: In this paper, the development of foam concrete (FC) and cellular lightweight concrete (CLWC) in Singapore is described. This technology is extremely useful for the developing countries in special areas of construction such as residential and other non-commercial construction. FC and CLWC can be used for cast in place construction as well as precast construction. Cement based units such as blocks and tilt up panels can be prefabricated, and this assures a higher level of quality assurance for the constructed facilities.

1. INTRODUCTION

1.1. Light Weight Concrete Construction Methods

Lightweight Construction Methods (LCM) (also known as foam concrete (FC)/cellular lightweight concrete (CLWC)) were developed more than 60 years ago and since then have been used internationally for different construction applications. LCM has been used in the building industry for applications such as apartments, houses, schools, hospitals, and commercial buildings.

Foam concrete is a mixture of cement, fine sand, water and special foam, which, once hardened, results in a strong, lightweight concrete containing millions of evenly distributed, consistently sized air bubbles or cells. The density of FC is determined by the amount of foam added to the basic cement and sand mixture. Foam concrete is both fire- and water-resistant. It possesses high (impact and air-borne) sound and thermal insulation properties. Foam concrete is similar to conventional concrete as it uses the same ingredients. However, foam concrete differs from conventional concrete in that the use of aggregates in the former is eliminated. A foam aeration agent is used to absorb humidity for as long as the product is exposed to the atmosphere, allowing the hydration process of the cement to progress in its ever-continuing strength development.
1.2. Applications

The applications of LCM in civil infrastructure are diversified and include:
- Cast in-place for units of low cost terrace houses, high-rise buildings, and bungalows.
- Lightweight blocks for high-rise buildings.
- Panels and partition walls of various dimensions either pre-cast or poured in place.
- All types of insulation works, including cavity walls.
- Roofing and ceiling panels.
- Soundproofing applications.
- Pre-cast industrial and domestic building panels, both internal and external.
- Pre-cast/in-place exterior wall facades for all sizes of buildings.
- Foundations for roads and sidewalks.
- Subsurfaces for sports arenas, e.g., tennis courts.
- Void filling and infill sections between beams of suspended floors.
- Aircraft arresting beds.
- Crash barriers.
- Explosion-resistant structures.
- Highway sound barriers.
- Floating barges, jetties, walkways, fish cages and floating homes.
- Slope protection.

Below are some pictorial examples of applications:

Figure 1.1    Repairs on a bridge.
Figure 1.2  Façade tiles for an architectural application.

Figure 1.3  Cast in-situ walls.
Figure 1.4  Blocks.

Figure 1.5  Tilt-up panels.
Figure 1.6  Cast in-situ.

Figure 1.7  Exterior walls for residential construction.
Figure 1.8  Curtain walls for high-rise construction.

Figure 1.9  Low cost insulated walls for residential construction.
1.3 Benefits

There are number of benefits of LCM. These include:

- Reduces the dead weight of a structure from 1/3rd to ½ the weight of normal concrete.
- Can be manufactured to precise specifications of strength and density.
- Possesses excellent workability.
- Can be nailed, planed, drilled and sawed.
- Provides excellent heat and sound insulation.
- Can be applied with all traditional surface finishes: paint, tiles, bituminous membranes, carpets, etc.
- Moisture/water resistant and fire resistant.

1.3.1 Weight Reduction

The density of foam concrete ranges from 250 to 1,800 kg/m\(^3\), as compared to 2,400- 2,600 kg/m\(^3\) for conventional concrete. Therefore, the weight of a structure built with foam concrete would undoubtedly be reduced significantly, leading to tremendous savings in the use of reinforcement steel in the foundations and structural members.

1.3.2 Thermal insulation

Foam concrete with a density of 1,200 kg/m\(^3\), for instance, can produce a monolithic wall 5 times thinner that requires 10 times less raw material (by weight) and possesses 5 times superior insulation properties as compared to conventional concrete. The amplitude-ratio and phase-displacement of a 15 cm thick wall with a density of 1,100 kg/m\(^3\) causes the outside temperature of a building to take between 10-12 hours to reach inside. Such a duration, which is much longer than that of conventional concrete wall, results in the foam concrete being naturally air-conditioning. This results in tremendous savings in expensive electricity over the life of the building.

1.3.3 Fire Rating

A 13 to 15 cm (5-6 inch) thick wall made of 1,100 kg/m\(^3\) density LCM has a fire endurance of 5-7 hours. The same degree of endurance is achievable with a 400 kg/m\(^3\) density LCM that is only 10 cm thick. LCM is non-combustible, and the air embedded in LCM attributes to the high fire-rating.

1.3.4 Sound Insulation

LCM is a perfect impact and air-borne sound absorbing concrete and thus is highly suitable for partition walls and floor screeds/foundations.
1.3.5  Savings in Material

A reduction in dead weight contributes substantially to savings in reinforcement steel in foundations. Therefore, the overall quantity of steel reinforcement in LCM can be reduced by as much as 10%. Savings are also substantial in transportation, crane- and man-handling related activities as well as in raw materials, as no gravel is required to produce LCM, only the sand and cement mortar/paste subsequently embedded in the foam (air). Casting very slender walls can optimize the amount of concrete used, which also results in using a very thin layer of plaster. For certain applications, no plaster is required, and gypsum putty is directly applied before painting. Walls as thin as 50 mm can also be cast. The high flow ability of LCM makes vibration unnecessary, and thus requires vibrating equipment/accessories.

1.3.6  Savings in Manpower

Only a few semi-skilled workers are needed to produce LCM concrete for the casting/pouring of panels, blocks, or even complete walls for houses. In producing LCM, steelworks, formworks, brick laying and cement renderings do not constitute major site activities, and therefore the related workers are not required. Workers are only needed to set up cost-saving and reusable formworks, and then to remove them for the next erection / casting.

1.3.7  Life span of Cellular Lightweight Concrete

Cellular Light Weight concrete has a life-time span (minimum 100 years). Previous investigation has shown that sectioned blocks of cellular concrete cast 10 years ago indicated only 75 percent of the hydrated Cement. It is expected that the strength would continue to increase with continuing hydration. The use of LCM in many cases has eliminated the use of products like clay bricks, conventional concrete blocks and other insulation materials.

1.3.8  Self- Leveling Concrete Properties

Due to the absence of gravel and the ball-bearing effect of the foam, LCM possesses a high degree of flow-ability. It is also called Self Leveling Concrete. No vibration is thus required. LCM completely fills all gaps and voids in the concrete or mould, fully embedding any hoses, tubes, electrical conduits, windows and door frames, when cast in place. In addition to mixing and pumping of light weight concrete LCM offers a mobile mixing and pumping unit, discharging mixes at approximately 12 m$^3$ of LCM per hour at 40 m height.

1.3.9  Fast Track Construction Method

The rapid mixing and high fluidity of LCM facilitates result in speedy cast-in-place building structure. With the application of vertical formwork to cast complete houses in place,
omission of vibrating equipment results in the entire walls and roof slab of a building being filled in one step. Openings (or the actual frames) for doors and windows, and ducting and conduits for sanitary and electrical services can be cast in place and firmly embedded in the Cellular Lightweight Concrete.

2. PRODUCTION AND CURING

2.1 Foaming Agent

The LCM foaming agent is based on a protein hydrolisation and is biodegradable. It causes no chemical reaction with the surrounding matrix but serves solely as a wrapping material for the air to be encapsulated in the concrete (mortar).

2.2 Production Procedures

The extremely high stability and stiffness of the LCM foam allows any density of LCM concrete, from as low as 250 kg/m$^3$ to 1800 kg/m$^3$, to be produced with an optimum ratio of strength-to-density. The possible wide range of densities achievable thus offers multiple and diversified applications, such as on-site mixing, off-site mixing, prefabrication, precast or cast in place.

2.3 Curing

LCM requires a curing means and period identical to that of conventional concrete. It is essential, as in conventional concrete, that cement-based elements have moisture for hydration at an early age. This is particularly true in the presence of direct sunlight that is known to cause rapid dehydration of concrete surfaces; curing compound can be applied as an alternative barrier.

2.4 Skim Coating

LCM requires no plaster, and a normal water-repellent paint suffices. However, where desired, LCM can hold plaster very well, offering superb adhesive properties. It is also possible to apply wallpaper directly onto the surface. Nevertheless, skim coating is highly recommended with LCM before the application of normal paint.
3. Material properties

3.1 Strength

3.1.1 Compressive Strength

An average compressive strength of 2.86 MPa (415 psi) has been achieved on 650 kg/m$^3$ density LCM cubes following 28 days of the standard water-cure. Tests done to date on other densities revealed that a 28-day strength exceeding 18 MPa (2610 psi) is achievable depending on the density of the mix. A compressive strength of more than 20 MPa (2900 psi) is obtainable with the addition of silica fumes, polypropylene fibers and steel mesh reinforcements, for special applications in which more compressive strength is required.
Since blocks made from LCM are 1/3 to ½ the weight of normal concrete blocks, for the purpose of bearing the self-load of the LCM block-wall, blocks of compressive strength 300-450 psi (0.21 – 0.31 MPa) are used, as compared to conventional blocks of 600-800 psi (0.42-0.56 MPa). The 28-day compressive strength and dry density of cellular concrete is shown in Figure 3.1. Strengths of 16 MPa are achieved which is by ACI 318-05 definition still not structural concrete defined to be concretes with strengths greater or equal to 17.5 MPa. Note that with higher cement content strengths of up to 40 MPa can be achieved.

![Figure 3.1](image1.png)

**Figure 3.1** 28-day compressive strength and dry density of cellular concrete.

The 28-day compressive strength for various types of cements used in cellular concrete is shown in Figure 3.2.

![Figure 3.2](image2.png)

**Figure 3.2** 28-day compressive strength for various types of cements used in cellular concrete.
3.1.2 Thermal Conductivity and Fire Resistance

The variation of thermal conductivity with the dry density of cellular concrete is shown in Figure 3.3.

**Figure 3.3** The variation of thermal conductivity with the dry density of cellular concrete.

**Figure 3.4** shows the fire rating measured in hours for various thicknesses of cellular concrete.

**Figure 3.4** Fire resistance in hours versus the thickness of cellular concrete.
3.1.3 Drying Shrinkage and Water Absorption

Figure 3.5 shows the drying shrinkage of cellular concrete with time.

Figure 3.5 Drying shrinkage with time for cellular concrete.

Figure 3.6 shows that foam concrete has less than 1/3 the water absorption as that of normal concrete.

Figure 3.6 Water absorption for normal concrete and foam concrete.
3.2 Lifespan of Foam Concrete

Foam concrete has a life span of minimum 100 years. Previous investigation has shown that in sectioned blocks of foam concrete cast 10 years ago, only 75 percent of the cement was hydrated. It is expected that the strength of these blocks would continue to increase with continuing hydration. The use of LCM in many cases has eliminated the use of products like clay bricks, conventional concrete blocks, and other outdated insulation materials.

4. APPLICATIONS

4.1 Ease of Application

Due to the absence of gravel and the ball-bearing effect of the foam, LCM possesses a high degree of flowability. No vibration is thus required. LCM completely fills all gaps and voids in the concrete or mould, fully embedding any hoses, tubes, electrical conduits, windows or door frames.

In addition to the mixing and pumping of lightweight concrete, LCM offers a mobile mixing and pumping unit, discharging mixes at approximately 12 m$^3$ of LCM per hour.

4.2 Speed of Application

The rapid mixing and high fluidity of LCM facilitates speedy casting of building elements. With the application of vertical molds to cast complete houses in place, omission of vibrating equipment results in the entire walls and roof slab of a building being filled in one step. Openings (or the actual frames) for doors and windows as well as ducting and conduits for sanitary and electrical services can be cast in place and firmly embedded in the foam concrete.

4.3 Construction Issues

As this material is lighter, the constructability is easier and faster. It seems that there are no adverse construction issues that are significant at this time.

5. SUMMARY AND CONCLUSIONS

This paper presented the results of some of the properties of foam concrete and cellular lightweight concrete that was recently developed in Singapore. FC and CLWC can be used for cast in place or precast construction. Cement based units such as blocks and tilt-up panels can be pre-fabricated, assuring a higher level of quality assurance for the constructed facilities.

ACKNOWLEDGMENT

The authors thank LCM Technologies for providing support.